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U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

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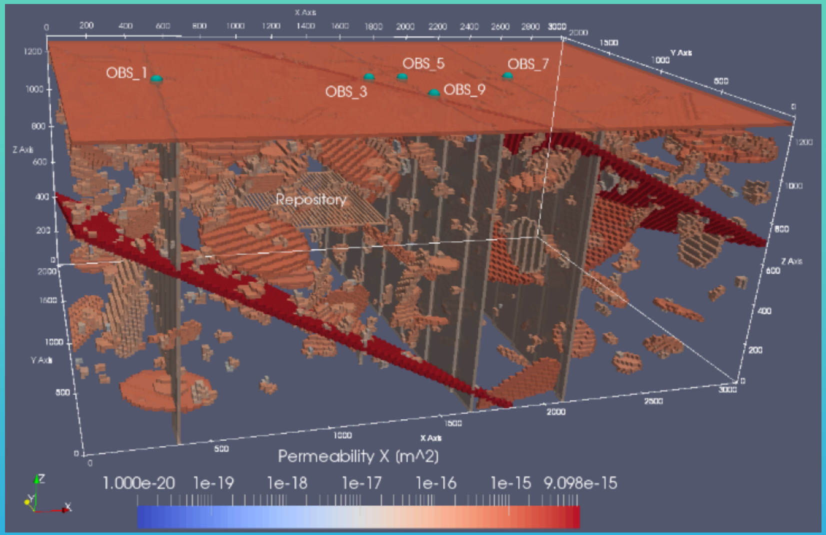

Respirable Aerosol Transmission through Stress Corrosion Crack-Like Geometries

SAND2022-#### PE

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Cooperative Severe Accident Research Program and
MELCOR Code Assessment Program
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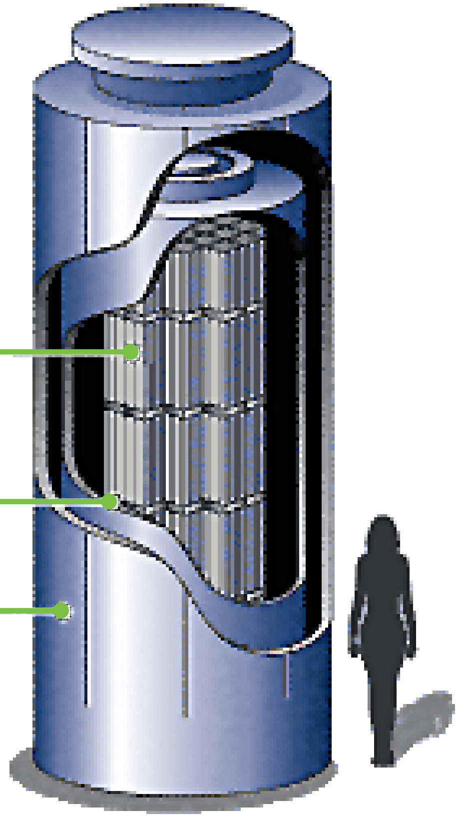
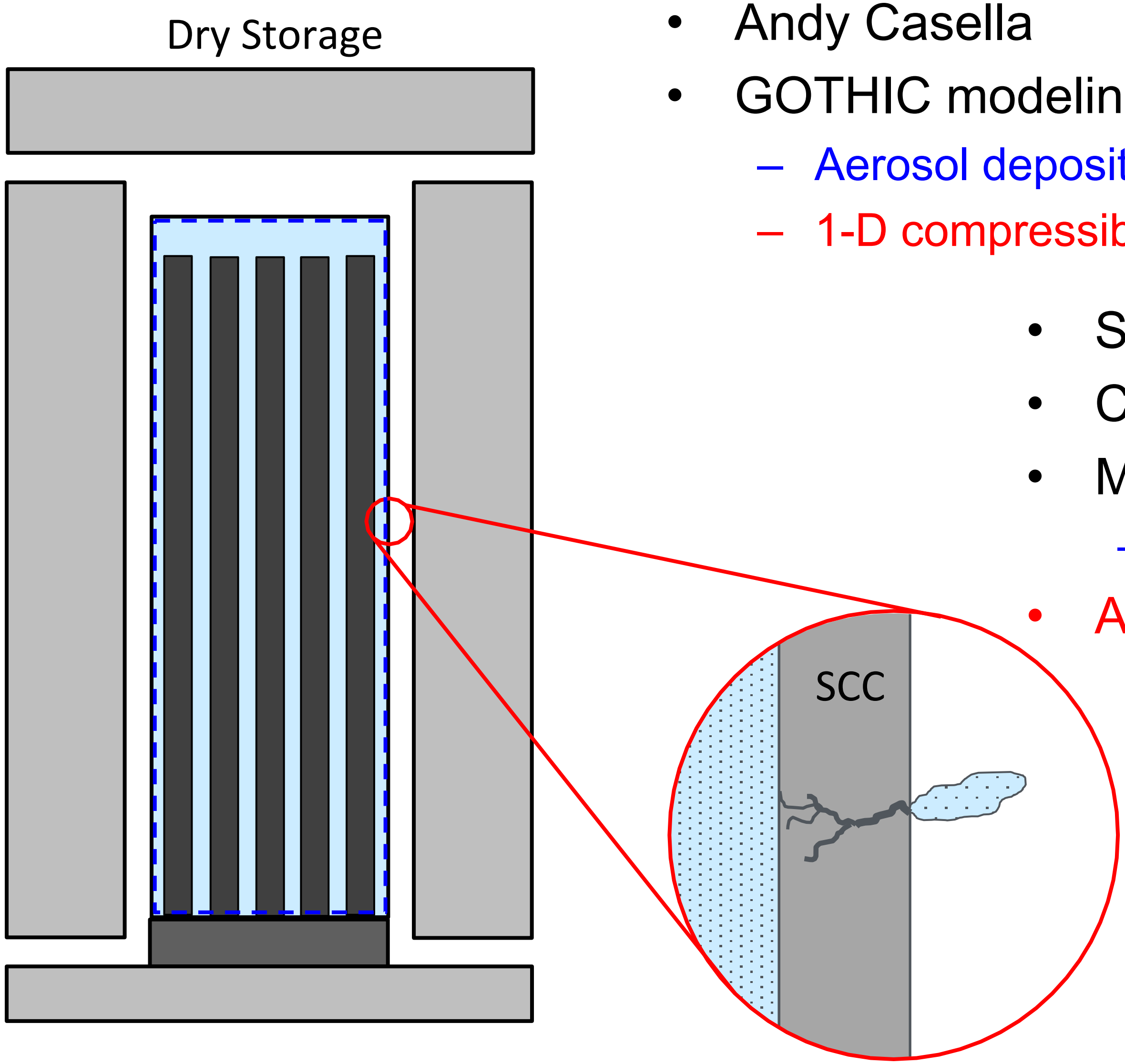
Objective



Source: www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html

- Mimic aerosol transport through a stress corrosion crack (SCC)
  - Pressure-driven flow
    - Prototypic canister pressures
    - Near-prototypic canister volume
- Explore flow rates and aerosol retention of an engineered microchannel
  - Characteristic dimensions similar to those of SCCs
    - Slot orifices – rectangular microchannels
    - Divergent nozzle – linear transition from inner to outer characteristic crack dimensions
- Measure mass flow and aerosol concentration
  - Upstream and downstream of microchannel
  - Simplified geometry with well-controlled boundary conditions

Collaborative Modeling and Testing



- Andy Casella
- GOTHIC modeling
  - Aerosol deposition in canister (planned work)
  - 1-D compressible flow model for SCC

Pacific Northwest NATIONAL LABORATORY

- Sam Durbin
- CFD internal flows (Fred Gelbard)
- MELCOR modeling (Jesse Phillips)
  - Aerosol deposition in canister
- Aerosol transmission testing (this presentation)

Sandia National Laboratories

- Yadu Sasikumar
  - Previous efforts by Stylianos Chatzidakis
- 1st principles modeling of aerosol transport/depletion in microchannels

OAK RIDGE National Laboratory

Previous Work

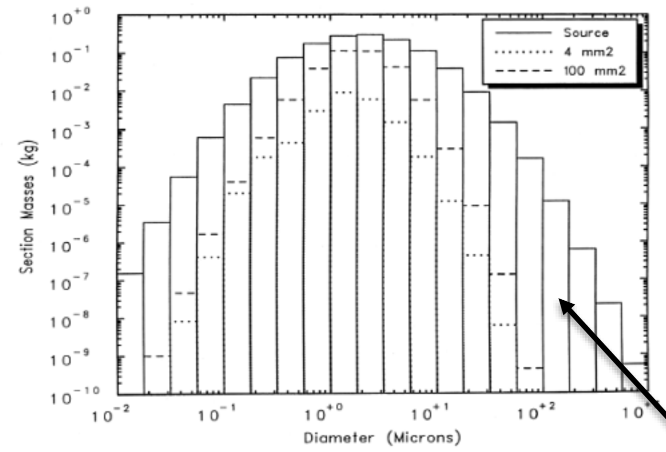


Figure 7.10 Size distributions of the particles sourced into the TN-12 cask from failed spent fuel rods, and of the particles that escaped from the cask through 4 and 100 mm[2] cask failures.

These results from MELCOR

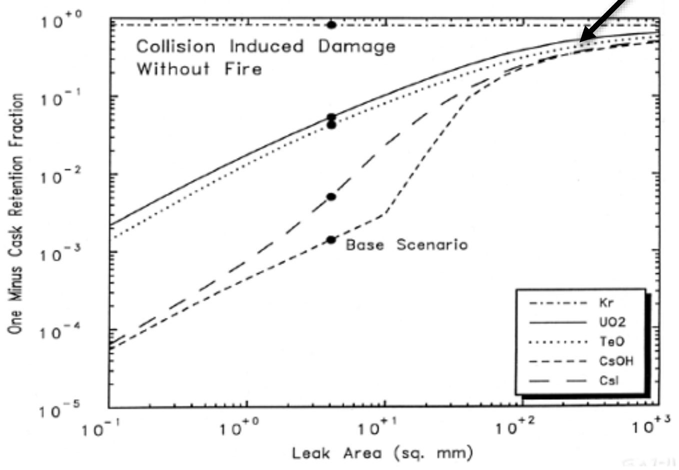
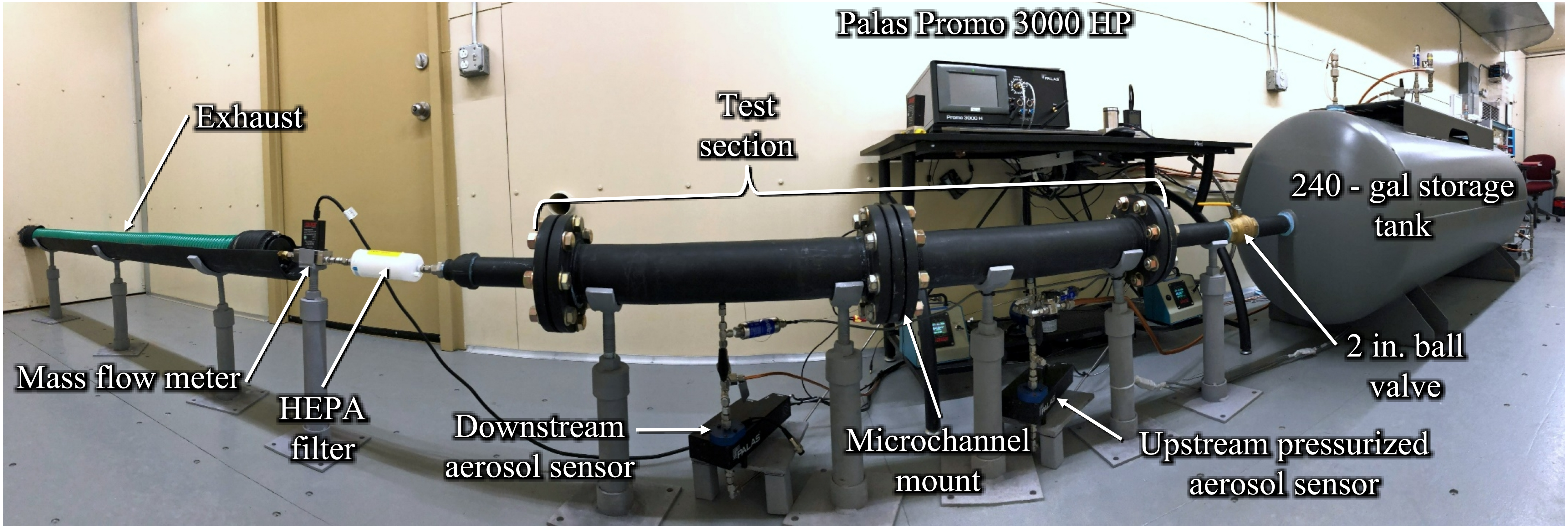


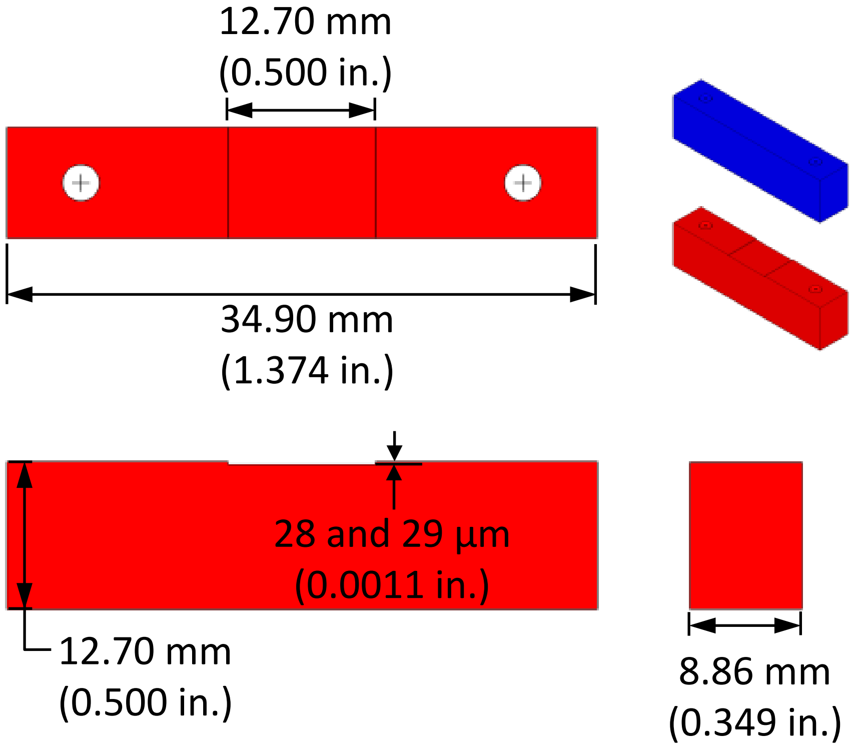
Figure 7.11 Dependence of Cask-to-Environment Release Fractions (1.0 – Retention Fraction) on the Size of the Cask Failure (leak area).

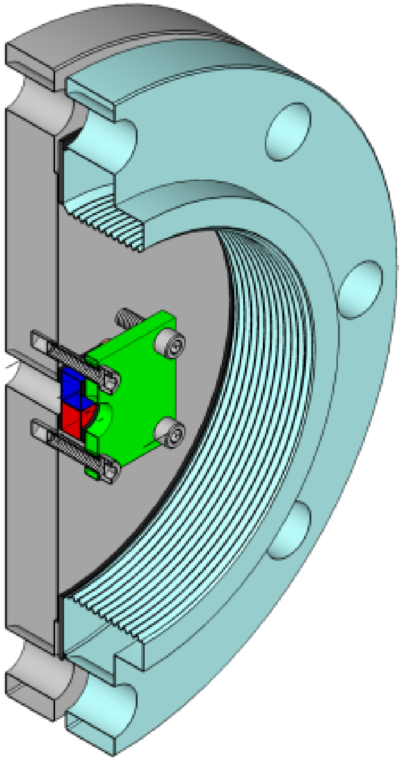
- Transportation accident work usually referenced
  - Figures on left from Sprung, J.L., et al., Reexamination of Spent Fuel Shipment Risk Estimates, NUREG/CR-6672
- Several assumptions not appropriate for storage
  - Orientation
    - Transport: Horizontal
    - Storage: Majority are vertical
  - Aerosol depletion
    - Transport: Primarily from gravitational settling
    - Storage: Most designs have strong internal convection limiting gravitational settling
  - Hypothetical leak path
    - Transport: Breach in transport overpack
    - Storage: Through-wall SCC in canister shell

Test System Photograph

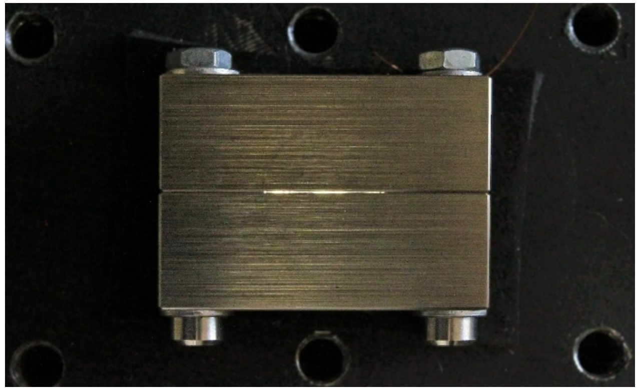


Engineered Microchannel



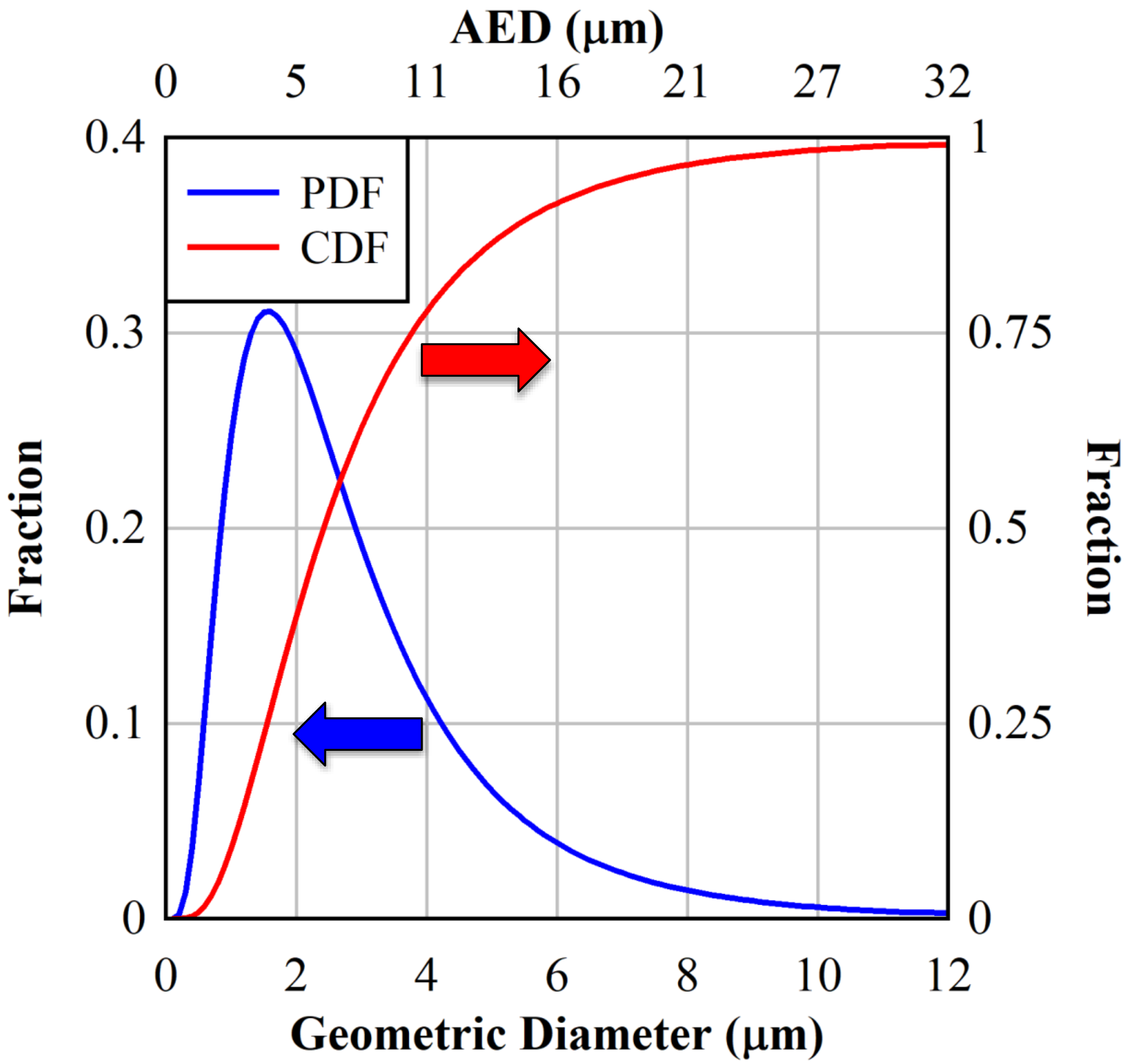


Isometric view of mounted microchannel on upstream side



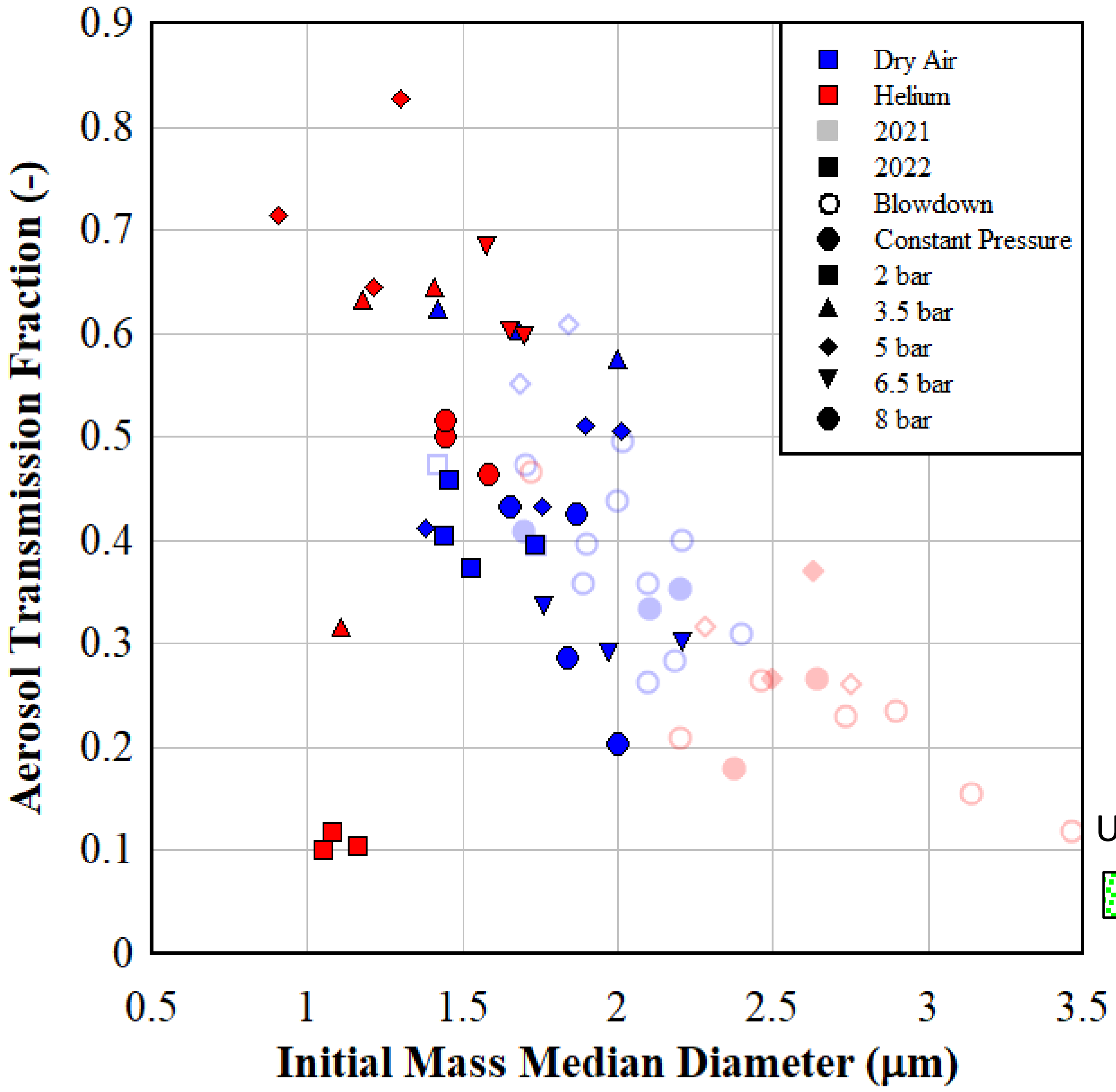
- Microchannel formed with paired blocks
  - High-precision gage blocks
  - Electrical discharge machined to form channel
  - Dimensions
    - Flow length: 8.86 mm (0.349 in.) long
    - Channel width: 12.7 mm (0.500 in.) wide
    - Channel height:
      - Original slot channel: 28.9 µm (0.0011 in.)
      - New slot channel: 27.7 µm (0.0011 in.)
- Bolted together to form microchannel
- Replaceable test section
  - Ultimately conduct experiments with representative SCCs

Surrogate Selection

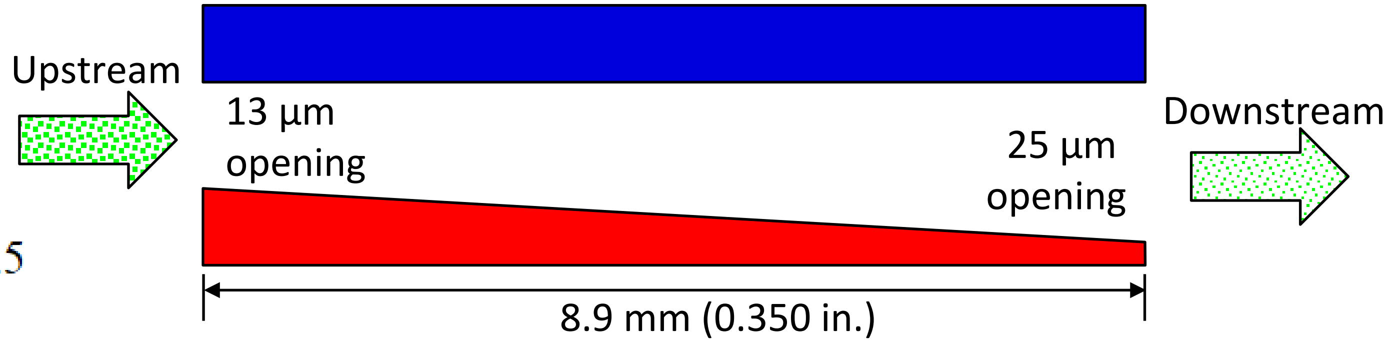


- Cerium oxide (CeO_2) chosen as surrogate
  - $\rho_{CeO_2} = 7.22\ g/cm^3$
  - $\rho_{SNF} \approx 10\ g/cm^3$ (Spent fuel)
- Particle size distribution
  - Mass median diameter (MMD)
    - MMD = 2.4 μm
  - Geometric standard deviation (GSD)
    - GSD = 1.9
  - ~75% particles (by mass) respirable
    - AED < 10 μm

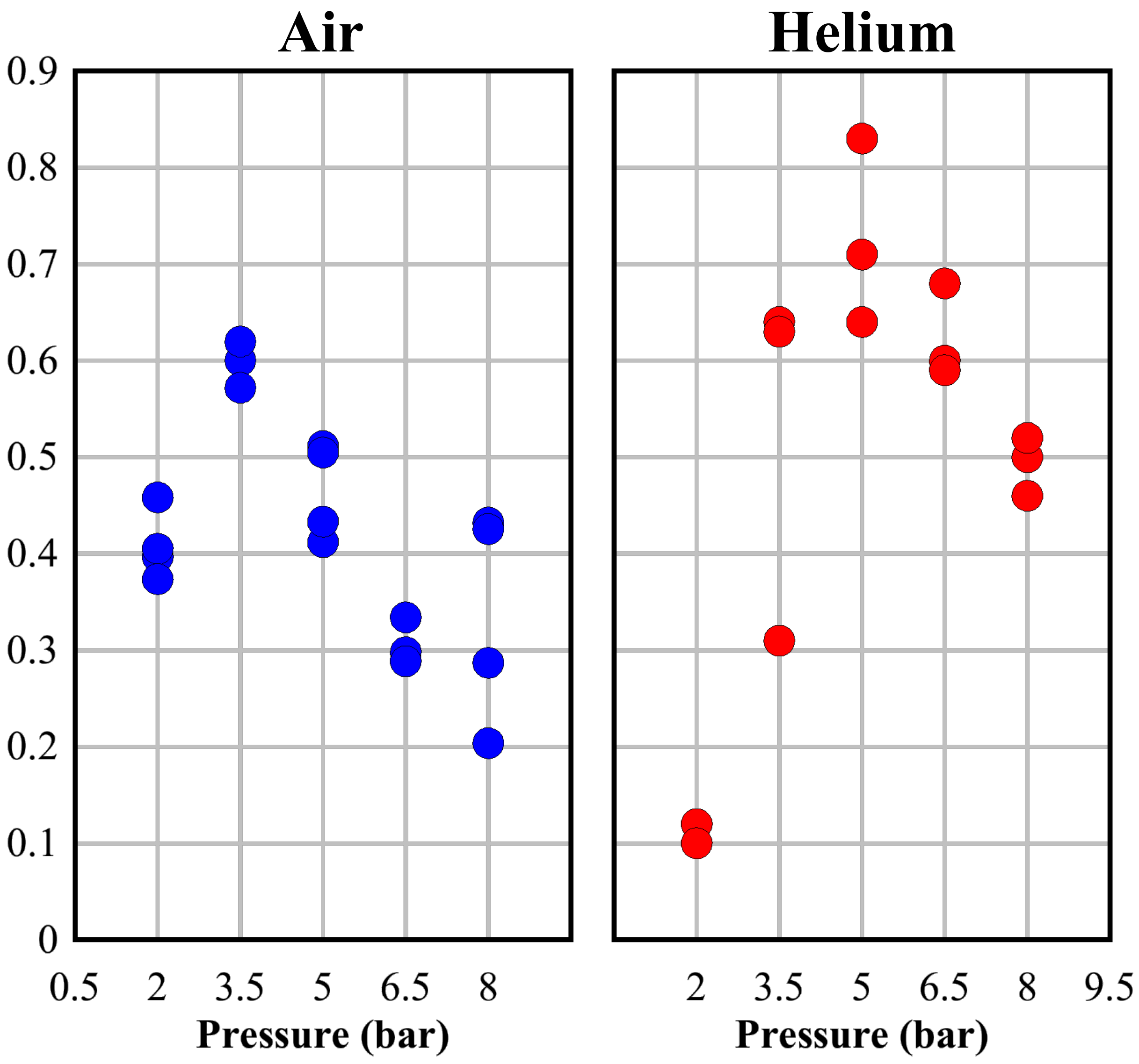
Preliminary Aerosol Transmission Results



- Transmission of aerosols ↓ as MMD_o ↑
  - Transmission ranged from ~0.1 to ~0.8 over entire test series
  - Air or helium as carrier gas
- SCC simulated with linearly diverging microchannel
  - Upstream to downstream transition
    - 13 to 25 µm
  - Simulated crack acts as flow restrictor and filter

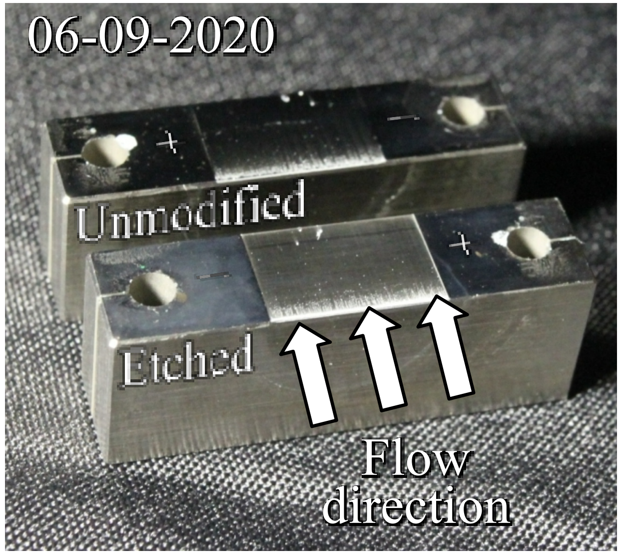


Carrier Gas Effects



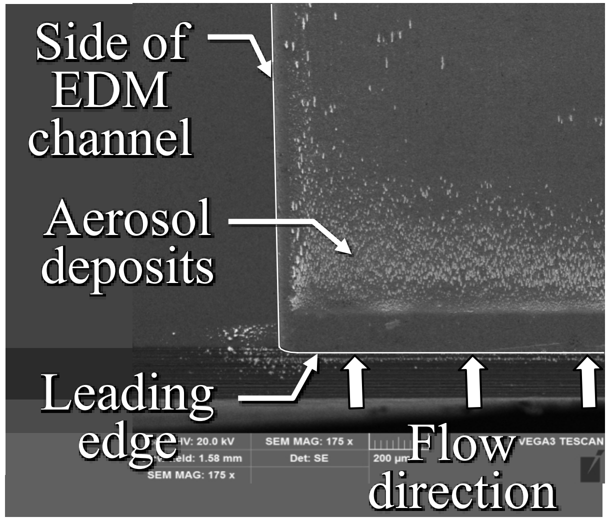
- Air
  - Peak transmission at 3.5 bar
  - Tight grouping with exception at 8 bar
- Helium
  - Peak transmission at 5 bar
  - Outlier at 3.5 bar
  - 2 bar requires use of cover gas
    - Downstream concentration diluted
      - Accounted for in analysis
    - Flow field may be significantly different

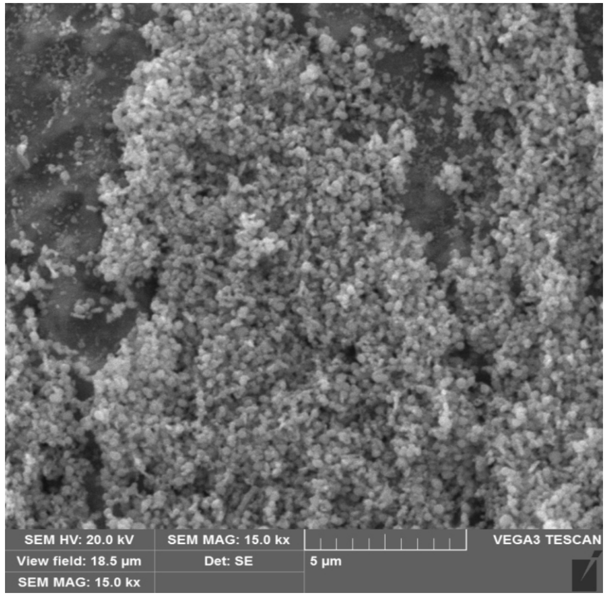
Aerosol Deposits



Photographs

- Aerosol deposits on microchannel
  - Five tests show similar behavior
    - Streaking
    - “Snowball” accumulation
  - Upstream leading edge
    - More accumulation
  - Streaking due to agglomerate migration
    - Spikes in downstream mass concentration
      - Believed to be from occasional breakthrough





SEM Images

Independent Modeling

Two independent thermal-hydraulics codes, originally written for analysis of nuclear power plants, have been configured to examine aerosol transport inside of a vertical spent fuel storage canister.

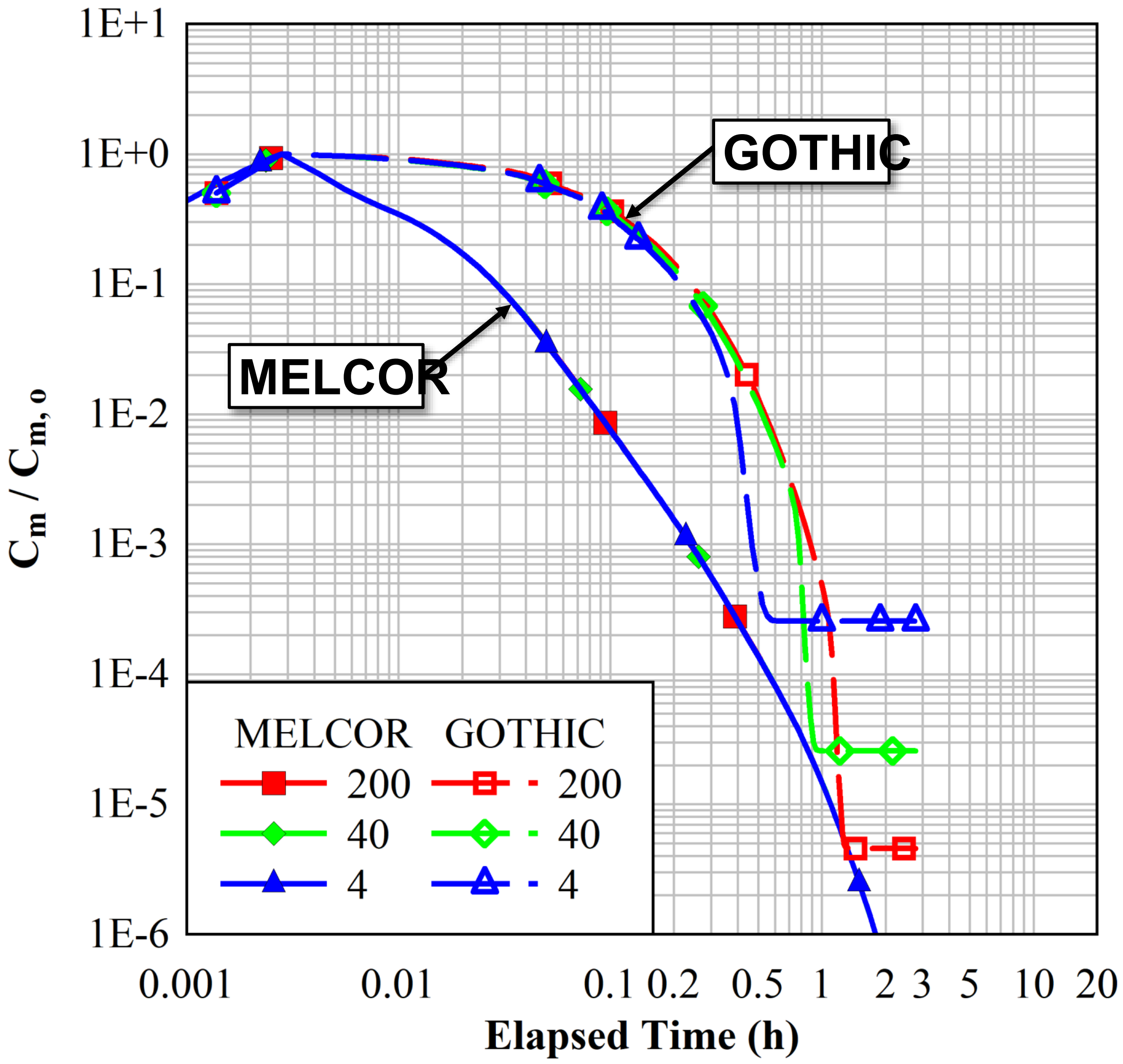
GOTHIC

- Generation of Thermal Hydraulic Information in Containment
- Integrated finite volume, general-purpose thermal-hydraulics code
  - Used for design, licensing, safety, and operating analysis of nuclear power plants and components
  - Lumped and multidimensional geometries
  - Tracks evolution of multiple drop/aerosol fields based on transport, phase change, and interactions with other fields and surfaces

MELCOR

- Coupled thermal-hydraulic and risk-significant phenomena modeling in a system-level accident code
  - Developed at SNL for US Nuclear Regulatory Commission (NRC)
- Designed to simulate reactor, auxiliary equipment, and other nuclear components
- Uses a “control volume” approach to solve thermal-hydraulics
  - Tracks fuel and fission product release and transport

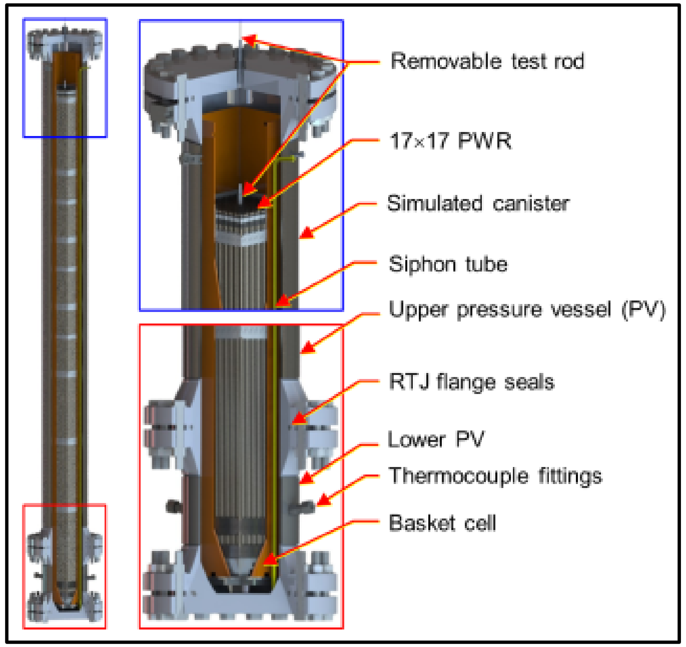
Aerosol Depletion in SNF Canister



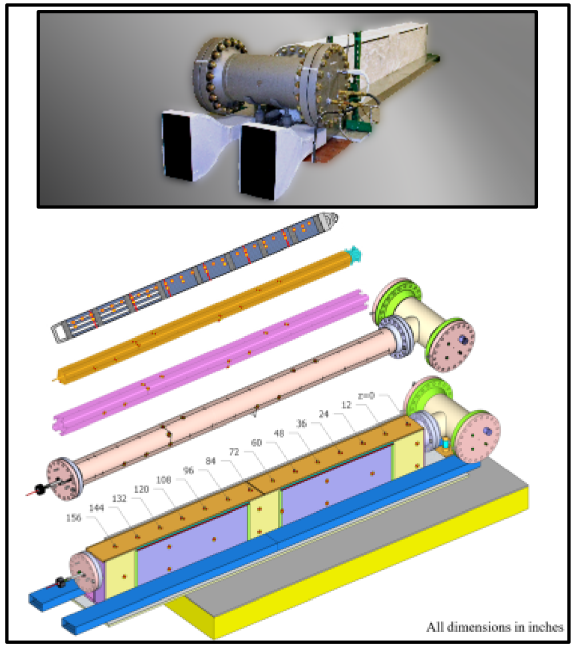
- Normalized depletion nearly independent of initial mass concentration ($C_{m,o}$)
  - 1% fuel failure → ~200 mg/m^3
    - ~50 mg/m^3, STP
- Lognormal particle size distribution
  - MMD_o = 3.46 µm and GSD_o = 2.24
    - Based on measurements from Hanson, *et al.*, 2008
  - Plateauing GOTHIC results from imposition of minimum count density
- **Nearly 6 orders of normalized aerosol mass depletion in less than 2 hours**

Summary

- Explored flow rates and aerosol retention in a diverging microchannel
  - Characterize hypothetical aerosol-laden flow through an SCC
  - Large parameter space for aerosol transport under conditions of interest
  - Preliminary results
    - **Aerosol mass transmission ranged from ~10 to 80%**
- Preliminary modeling (FY21) shows **significant depletion in less than 2 hours** from fuel-to-canister release
  - Some differences in codes remain
- Future work
  - Continued testing of diverging microchannel
  - Prepare for testing of lab-grown cracks
  - Unify input conditions between codes
  - Explore options for **validation testing using DOE-sponsored apparatuses**
    - Advanced Drying Cycle Simulator
    - Horizontal Dry Cask Simulator



ADCS – Vertical 17×17 PWR



HDCS – Horizontal 9×9 BWR